Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 20, No. 1, pp. 104-112, February 28, 2014, ISSN 1229-3431(Print) / ISSN 2287-3341(Online) http://dx.doi.org/10.7837/kosomes.2014.20.1.104

Design and Performance Evaluation of a 10kW Scale Counter-Rotating Wind Turbine Rotor

Anh Dung Hoang* · Chang-Jo Yang**†
* Graduate School, Mokpo National Maritime University, Mokpo, 530-729, Korea
** Department of Marine System Engineering, Mokpo National Maritime University, Mokpo, 530-729, Korea

10kW급 상반전 풍력터빈 로터의 설계와 성능 평가에 관한 연구

황안둥* · 양창조**†
* 목포해양대학교 대학원, ** 목포해양대학교 기관시스템공학과

Abstract : *The counter-rotating approach on wind turbine has been recently put in interest for its certain advantages in both design and performance. This paper introduces a study on a counter-rotating wind turbine designed and modeled using NREL airfoils S822 and S823. The aims of the study is to evaluate and discover the performance of the counter-rotating system, and compares to that of single rotor turbine of same design using numerical simulation. The results show higher performance of the counter-rotating system compared with single rotor case at TSR 3 to 5 but lower performance at higher TSR. This is due to the interaction between upstream and downstream rotors. Thus, the counter-rotating turbine is more efficient at low rotor rotational speed.*

Key Words : *CFD, Wind turbine, Horizontal axis wind turbine(HAWT), Counter-rotating wind turbine(CRWT), Energy, S822, S823*

요 약 : 상반전 풍력터빈은 설계와 성능 관점에서 최근 각광을 받기 시작하고 있다. 본 논문은 NREL S822, S823을 이용하여 설계 및 모델링한 상반전 풍력터빈에 대해 연구를 수행하였다. 본 논문은 수치해석 기법을 통하여 단일 풍력터빈과 상반전 풍력터빈을 각각 설계하고, 그 성능을 다양한 조건에서 비교하고자 하였다. 그 결과 상반전 풍력터빈은 단일 풍력 터빈에 비해 TSR 3~5 영역에서 보다 높은 성능계수를 나타냈으며, 그 보다 더 높은 TSR 영역에서는 낮은 성능계수를 나타내었다. 이것은 로터 상・하류의 간섭의 간섭 때문이며, 또한 본 연구에서는 낮은 영역의 TSR에서 운전되는 상반전 풍력터빈의 유효성을 함께 보였다.

핵심용어 : 전산유체역학, 풍력터빈, 수평축터빈, 상반전 풍력터빈, 에너지, S822, S823

1. Introduction

Recently, as man's demand of energy continuously grows, wind power becomes one of the sustainable energy sources that have been being investigated thoroughly for years. Although the practical concept of wind turbine was introduced in 9th century, the first electricity generating wind turbine has just been manufactured in 1887, and during 19th century wind turbine became more and more developed (Burton et al., 2011). Nowadays, wind turbine continues to be an interesting topic for researches and scientists to put their effort on in order to improve its operating performance. In general, wind turbine has proved high potential as a present energy solution as well as the future power-generating device (Tangler et al., 1995).

The aim of wind power technology development is to improve performance and efficiency while reducing the cost for construction and maintenance. Most of practical wind turbine systems being applied all over the World are single rotor systems, especially the horizontal axis wind turbine (HAWT) which is simple in construction, has good reliability and durability and has much higher power coefficient than that of vertical axis design. In conventional single rotor turbine -

* First Author : had@mmu.ac.kr, 010-5678-3089
† Corresponding Author : cjyang@mmu.ac.kr, 061-240-7228

generator system, generator stator is stationary and the system simply generates electricity by connecting and transferring turbine's rotational movement to electric generator's rotor shaft. For years of improvement, enhancements have been made to these types of turbine, i.e. better aerodynamic characteristic of blades, reduced noise, better torque transmission efficiency, better electrical efficiency of generator unit, etc. However, despite of these improvements, single rotor turbines are not able to capture a high portion of the wind stream energy and convert it into electrical energy. Thus, an alternative design has been put into development for recent years, the contra-rotating wind turbine (CRWT), which has capability of overcoming the limitation of the efficiency of the single-rotor turbine without increasing the size of the rotor (Herzog et al., 2010). By adding a counter-rotated rotor and connecting it to electric generator's stator, an assembly of moving rotor and stator is formed. Hence, power output is increased due to such counter-rotating effect.

In this study, our model is a 10kW CRWT equipped with two rotors which rotate in opposite direction. The two rotors are designed with the same sizing and uses the same airfoil section. In details, NREL airfoil families including the S822 and S823 are applied for our wind blade. NREL airfoils are specially designed for HAWT because of their ability that minimizes the energy loss due to roughness effects. In this study, the designed blade consists of root airfoil (S823) and tip airfoil (S822) which are specialized for small turbine rated at 2-20kW scale. The simulation results show an improvement in power coefficient of the counter-rotating design compared with conventional single rotor design, which proves the dominance of CRWT in terms of performance with regard to sizing and wind condition. This design is suitable for small applications as households, small buildings, etc.

2. Principle and Design of CRWT

2.1 Fundamental Principle

The power developed in the turbine shaft when compared to the available energy in the wind is usually presented in the form of power coefficient, which is defined as:

$$C_P = \frac{P}{\frac{1}{2}\rho V^3 A} \tag{1}$$

The maximum C_P is 0.593 as calculated from Betz's theory (1919) that is comprised of an analysis of axial momentum equation and the mass continuity equation. In this theory, power coefficient is derived to a function of axial induction factor, or induction factor. An induction factor, a, is defined as the fractional decrease in wind velocity between the free stream (upstream) and the rotor plane:

$$a = 1 - \frac{V_d}{V} \tag{2}$$

And, power coefficient can be rewritten as:

$$C_P = 4a(1-a)^2 \tag{3}$$

As a increases from zero, the downstream flow speed steadily decreases until a = 1/2, meaning that the rotor has completely stopped and the theory is no longer applicable (Burton et al., 2011). It can be simply found that power coefficient reaches maximum at a = 1/3, where C_P = 16/27 (or 0.593). However, recent tests and researches have shown that practical turbines, i.e. the work of Hartwanger and Horvat (2008), are able to capture the power that is much lower than theoretical estimation. Thus, a large amount of the potential wind energy escapes without being harnessed. In fact, there are wake effects behind a single rotor which contain a large amount of unused energy. This unused extra energy can be extracted further by installing a second rotor in the wake region.

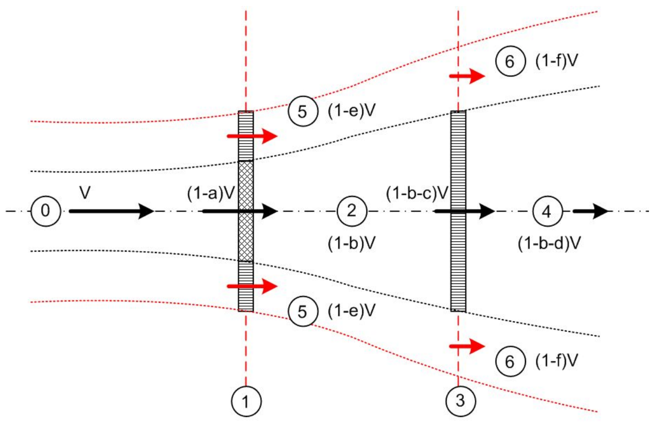

Fig. 1. Velocity variation over the stream tube.

Newman (1986) proposed a method to analyze the power coefficient of a horizontal axis turbine which consists of two rotor discs in series. It was found that the maximum power coefficient would increase to 64 % (Chantharasenawong et al., 2008). Fig. 1 shows the schematic view of stream tube over the double-rotor turbine. As flow passes through the rotors, wind speed varies with the stream tube. In this figure, other than *a*, *b*, *c*, *d*, *e* and *f* in turn represents the portion of wind speed deficit at different downstream locations, which are numbered from ① to ⑥ in the figure. After losing a portion of kinetic energy to the first rotor (expressed by induction factor *a*), wind speed reduces from *V* to *(1-a)V*. The second rotor is installed at the rear in order to capture this remaining energy.

However, due to the wake forming effect from the first rotor, some of the wind flow can escape the second rotor by moving to the far field directly and caries an amount of energy expressed by *(1-e)V* away. Thus, only the wind at the central region is able to contact the latter and possible energy can be extracted is expressed by *(1-b)V*. Certainly $a = b+e$. The same distribution happens when the flow passes the second rotor where wind speed is reduced to *(1-b-c)V*, then scattered over the field at downstream. By applying the same derivation method as in the single rotor case, power coefficient can be expressed as $C_P = f(a, b, c, d, e, f)$. The conditions at which maximum power ($C_P = 0.64$) is generated require the flow speed past the first rotor to be $0.8V$ (corresponds to $a = 0.2$) and the flow speed past the second (downstream) rotor to be $0.4V$ (corresponds to $b + c = 0.6$). Thus, Chantharasenawong's theory proved that CRWT can absorbed more power and is more efficient than single rotor turbine.

Since the wake behind the first rotor is rotating in the opposite direction to its rotational direction, the second rotor should rotate in the same direction as the wake in order to effectively capture the available energy therein. Thus, such composition is called counter-rotating. And as mentioned above, CRWT design allows its generator stator (magnet part) to rotate inversely with the rotor (coil part), thus increases the capability of generating more power than conventional generators which have stationary magnet part. Principle of this assembly is illustrated in Fig. 2. Besides, both rotors are geared using 1:1 ratio so that they can rotates with the same rotational speed. Currently, the counter-rotating concept is used on airplanes, boats, and submarines to increase efficiency while eliminating the asymmetrical torque faced by conventional rotors.

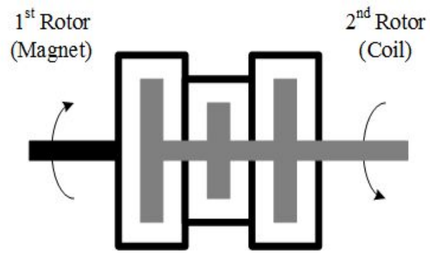

Fig. 2. Rotor shaft – generator connection.

2.2 Blade Design

A family of thick airfoils for 3 to 10 meter diameter, stall-regulated, horizontal-axis wind turbines, the S822 and S823, has been designed and analyzed theoretically by Somers (2005). The primary objectives of restrained maximum lift, insensitive to roughness, and low profile drag have been achieved. The constraints on the pitching moments and airfoil thicknesses have been satisfied. As the chosen turbine is a 10kW scale, considered as small wind turbine, it is suitable to apply the S822 and S823 airfoils in this study. The original airfoil profiles (Fig. 3) are applied and neither change nor modification has been made. The designed specifications for this family indicate a tip region maximum lift coefficient (C_L) of 1.0 and a minimum drag coefficient (C_D) of 0.01 for a Reynolds number of 600,000. The very low Reynolds number range for this family contributes to a higher min C_D and increases difficulty in achieving a high root airfoil maximum C_L (up to 1.2) for a Reynolds number of 400,000, which is approximate to our design in this study. For small turbines, the high flap and torsion stiffness required dictate that the S822 tip airfoil have a thickness of 16 % (Tangler and Somers, 1995).

However, in this study we raise this value up to 20 % to increase blade strength at tip region. Preliminary parameters for blade design are summarized in Table 1. The blade geometry is design using blade element momentum theory following Ingram's guidance (2011) and additional calculations. Aerodynamic characteristics of blade such as twist angle and axial flow induction factor are established as shown in Fig. 4 and Fig. 5.

Table 1. Design parameters

Parameter	Value
Design power	10 kW
Inflow wind speed	10 m/s
Air density	1.225 kg/m^3
Blade number	3
Desired tip speed ratio	6
Angle of attack at tip	5^o
Thickness at tip	20 %
Thickness at root	40 %
Rotor diameter	7.16 m
Hub diameter	0.6 m
Hub/Blade length ratio	11.93
Rotor to rotor distance (for CRWT)	7.16 m

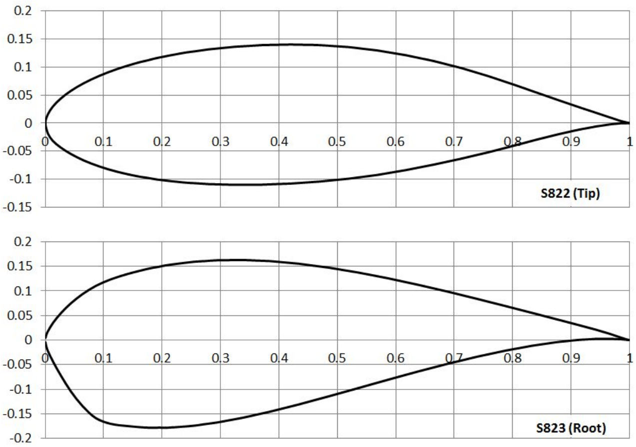

Fig. 3. Profiles of S822 and S823.

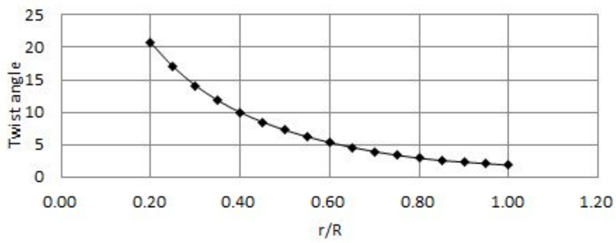

Fig. 4. Blade twisting angle.

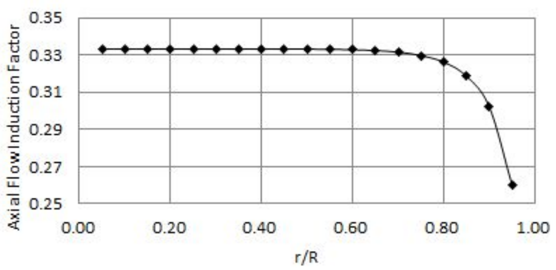

Fig. 5. Axial flow induction factor variation.

Originally, NREL recommends that the S823 for root region to be applied to 40 % of blade length (Tangler et al., 1995). This recommendation is applied to our blade with a certain change. Because the CRWT in this study is small size turbine, the region for S823 is set to 33.3 % that is enough for strengthening root part, another 33.3 % of blade body is modeled with the S822 as the tip region. The middle part that contributes to the last one-third of blade body is interpolated using modeling software's function. The purpose of this is to enhance the smoothness of the lower surface which is complex in geometry due to the profiles of airfoils used (Fig. 6). The completed 3D rendering for the rotor and blades is shown in Fig. 7.

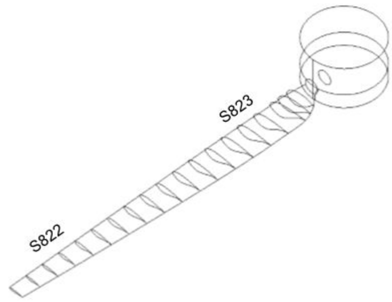

Fig. 6. Blade geometry.

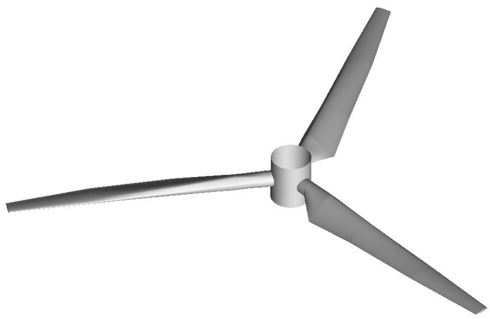
Fig. 7. Rotor 3D model.

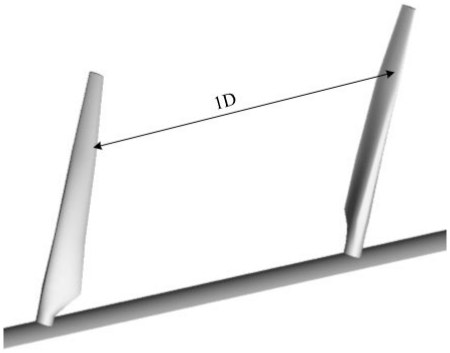

Fig. 8. CRWT assembly.

There are several options for counter-rotating assembly and these mainly differ in the second rotor structure. Some researchers choose higher number of blades, some prefers selecting different shape and size (usually bigger) for the second rotor, i.e. the assembly of Kumar et al. (2013). In our case, we aim to design a small CRWT that is compact in size. Thus, the second rotor is modeled exactly the same to the first one in terms of shape and size. Longer or broader blades shall improve the second rotor's performance but load on turbine structure will be increased as well. Compactness and simplex are the top priorities of the design presented in this paper. The space between two rotors is set to one diameter unit (1D) as shown in Fig. 8.

3. Numerical Simulations

3.1 CFD Approach

Based on various theories, aerodynamic researches and comparisons between experimental and computational studies, the wind turbine is either studied experimentally in a wind tunnel or investigated computationally using methods that belong to the field of computational fluid dynamics (CFD). These two approaches are closely linked and have certain advantages as well as disadvantages. Experimental and computational research provide results for better understanding of the flow physics and enable investigation of wind energy performance, a requirement in order to adjust the design of wind turbines to the unique aerodynamic conditions in the environment. As with all methods of analysis, the CFD approach has limitations which are essentially related to turbulence modeling. CFD simulation of wind turbine is reviewed as a virtual, multi-scale wind tunnel applied by the wind energy community from small to large scale. But all in all, the cost of a CFD analysis that is highly comparable to that of a wind tunnel experiment. Because of that significant advantage, we considered the CFD simulation, using commercial code ANSYS CFX, for our current study emphasizing on the performance of CRWT.

3.2 Meshing and Computational Domain

Computational simulations are carried out for both single rotor turbine and CRWT. In case of CRWT, the computational domain for the counter-rotating simulation consists of two individual domains, each contains one rotor. All domains are computationally discretized using hexa mesh. The counter-rotating domain has the mesh size of 2.53 million nodes. Hexa mesh is preferable for its well structured formation (Fig. 9).

Rotors in all cases are 3-bladed type, and generally, the blades in a rotor are the same in all aspects. Therefore, most of the turbine researchers are doing their simulations with only a single blade domain (periodicity of 120°). By referring to CFD workshops and documentations, compressor and turbines are analyzed in similar fashion. Torque of one blade with respect to the rotating axis is gotten from simulation and multiplies by respective number of blades and speed of rotation for power calculation. So, it is more convenient as the time and cost for computational calculation can be greatly reduced. This method is applied to our counter-rotating domain.

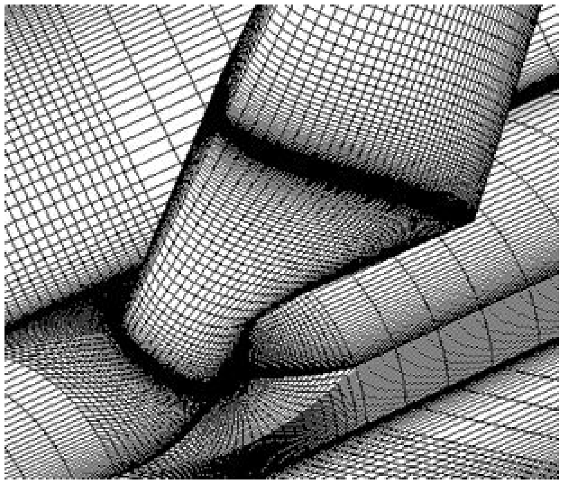

Fig. 9. Mesh formation around blade root.

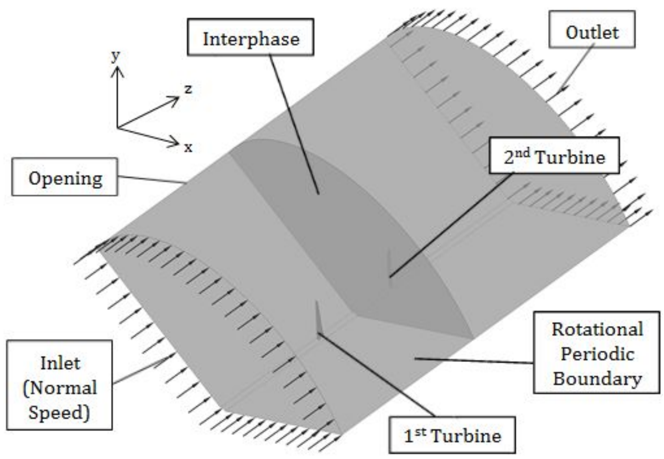

Fig. 10. Domain and boundary conditions.

The domain and its boundary conditions are illustrated in Fig. 10. Inlet boundary is normal speed and input value is set to 10m/s. Outlet boundary is static pressure. Both turbine blades are setup as free slip wall boundaries. The opening is the free flow boundary where air enters the flow-field. There are three interfaces boundaries, one is the interface between two rotor domains and the rest are rotational periodic boundaries which make up an angle of 120^o. The interface between two rotor domains are general connection, which is a powerful way to connect regions together in CFD simulation, especially for regions that have different rotation rates. The frame change/mixing model is stage which is more accurate than frozen rotor model, steady state solutions are then obtained in each reference frame. Domain size is 23 m (Length) × 12.5 m (Radius) which is large enough to capture the wake and pattern of the flow. All simulations are done in steady state. Shear stress transport (SST) turbulence model is used since it has high stability. For steady state calculations, maximum integration is set to 4000 to ensure convergence with convergence criteria of 1×10^{-5}.

4. Results and Discussions

4.1 Single Rotor Turbine Performance

Simulations are done at a varied range of tip speed ratio (TSR). In this study, turbine's TSR is changed by changing rotational speed (RPM). Tested TSR range is from 3 to 7, which is corresponded to rotor's RPM from 80 to 189 for inflow wind speed of 10 m/s.

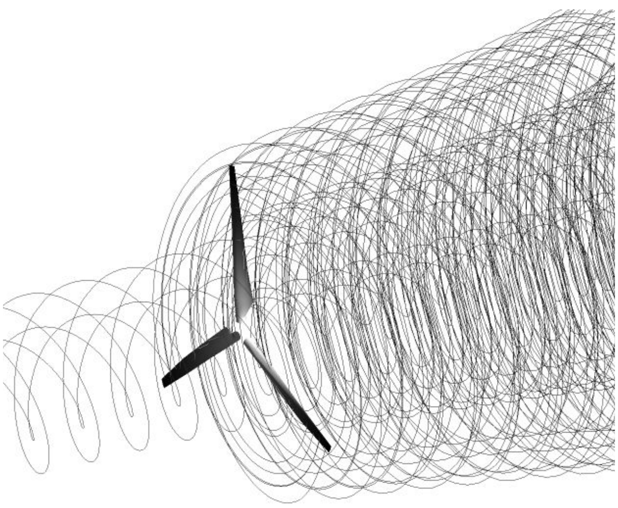

Fig. 11. Wake pattern in single rotor turbine (TSR 6).

Fig. 11 shows an illustration of turbine wake when it operates at TSR 6. In general, there is no abnormality found. The wake generated has unsteady flow pattern and it is reasonable as physical flow characteristic of wind passes through a turbine rotor, which can be relatively divided into three components: hub's wake, blade body's wake and tip's wake. Blade torque is extracted from the simulation result, hence power coefficient is calculated at different TSR value. The power performance curve of the single rotor turbine simulation is shown in Fig. 12. In this figure, the designed blade reaches maximum power coefficient of 0.37 at TSR 6. This value is 0.03 lower than the desired power coefficient given in advance. This difference is due to many factors that can be adjusted in CFD simulation. But generally, this is a relatively high power coefficient to be expected from this wind turbine design. The optimum operating range is found at TSR 5 to 7.

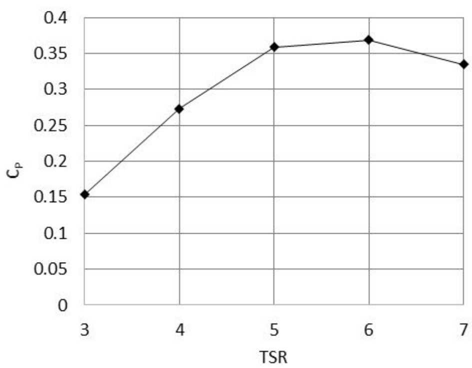

Fig. 12. Single rotor turbine performance.

4.2 CRWT Performance

The same simulation set up parameters are applied for counter-rotating case. Fig. 13 visualizes the wake in CRWT which also show normal wake pattern without any strange effect. There is an existent of turbulence and local vortex at hub-root region due to rotor-to-rotor interaction but it does not affect or disturb the flow of the whole stream tube. Both rotors rotate at the same rotational speed and are set from 80 rpm to 189 rpm like single rotor case.

Torque coefficient of CRWT is calculated and shown in Fig. 14, the calculation of single rotor turbine (at design wind speed of 10 m/s) is also added for convenient view and comparison. For CRWT, additional calculations are carried out at inflow wind speed of 8 m/s and 12 m/s. This is done for validation of numerical accuracy. Theoretically, torque or power coefficient vs

TSR curves should always maintain the same shape and trend regardless of dimensional value.

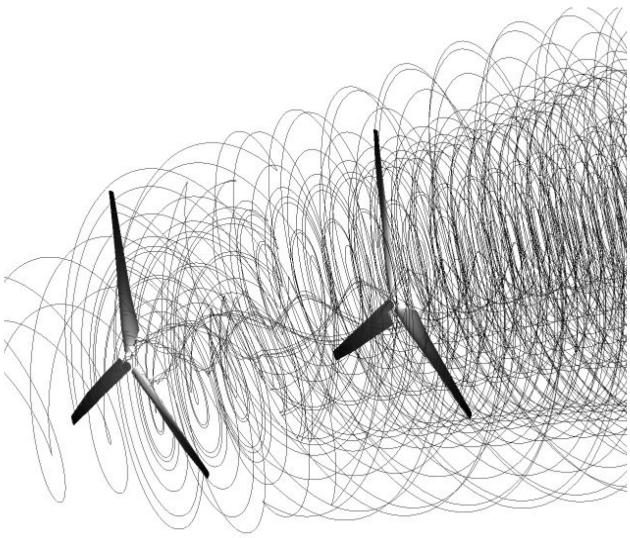

Fig. 13. Wake pattern in CRWT (TSR 6).

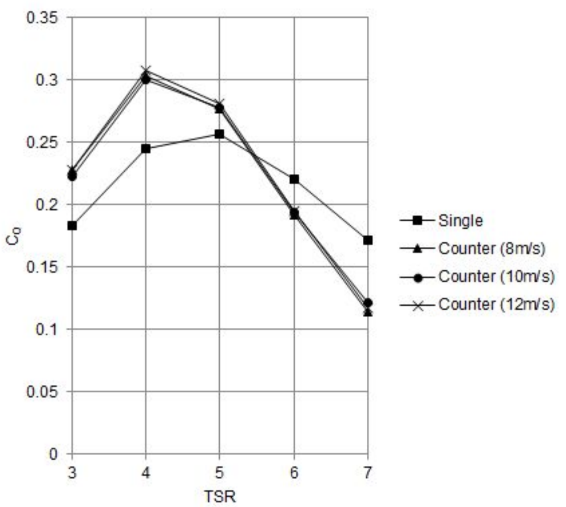

Fig. 14. Torque coefficient at different wind speeds.

But in Fig. 14, there are small variances at each calculation points. Practically, different inflow speeds can influence the torque at a chosen operating TSR. The influence may due to various practical effects, i.e. the increase of resistance, mechanical loss. In case of CFD simulation, the existent of this variance is mainly due to numerical error that originated from computational structure as meshing, turbulence model. Since turbulence intensity is set to 5 % at the inlet in all cases, small differences in results are reasonable. In general, the curves have similar characteristics with acceptable error. Compared to single rotor turbine, the CRWT have much higher torque at low TSR region (TSR < 5.5). However, at higher TSRs, CRWT is no longer generating high torque. This is due to the complex interaction between two rotors which causes the decrease of performance on the second one, consequently drags the overall generated power down. In case of single rotor, without the effect of second rotor, high torque is maintained at high TSR region.

The overall comparison of power performance between CRWT and single rotor turbine is shown in Fig. 15. All the power coefficient values calculated at original design wind speed of 10 m/s. When operating in counter-rotating formation (when the second rotor is added), first rotor's efficiency has a certain decrease at all TSRs. And with the support of second counter-rotated rotor, the overall performance of the CRWT is increased at low TSRs. But this high performance is no longer maintained at high TSRs due to the interaction explained above. The curves' patterns are similar with those of torque coefficient. Optimum TSR for CRWT is found at TSR 5, where the power coefficient reaches about 0.4. In fact, both rotors of the CRWT are the same in design, the only difference is opposite blade geometry for counter-rotation. Hence, at the current calculation condition, the second rotor's capability cannot be completely utilized since the wind flow's characteristics are completely changed after going through the first rotor, i.e. angle of attack, pressure and force distribution. Thus, the CRWT design in this paper is able to capture about 2-8 % more of available wind energy. Herzog et al.(2010) carried out similar work and experimentally confirms that his CRWT can capture 9 % more energy than single rotor turbine. Herzog also states that there is strong aerodynamical interaction between two rotors that influences the overall performance of CRWT. Nevertheless, a conventional permanent magnetic synchronous generator consists of fixed stator and moving rotor, but CRWT can adopt a counter-rotating stator and rotor, which is possibly able to generate higher electric energy.

In summary, this studies provide an evidence to look closer at the concept of counter-rotating system to eventually produce quantitative comparison to single-rotor turbine. Energy capture in the rotor holds greate potential as its maximum overall power coefficient reaches 39 %. These results help contributing to the present development of wind turbine, especially the counter-rotating approach, as the future potential energy conversion machinery.

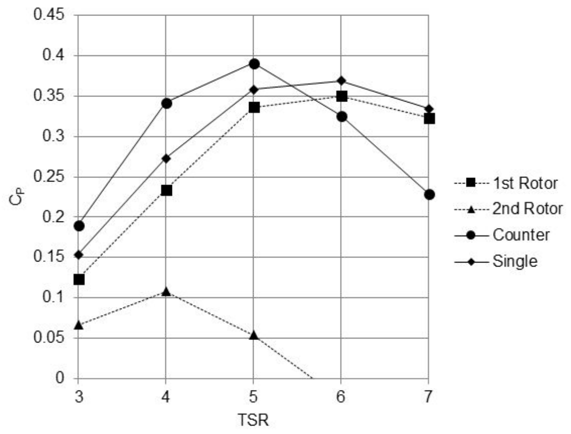

Fig. 15. Overall power performance as a function of TSR.

5. Conclusions

This paper introduces part of author's works about the counter-rotating turbine. To summarize the work presented above, conclusions are made as below.

1) In CRWT, each individual rotor has lower efficiency compared with single rotor turbine performance. This is due to the interaction between rotors themselves when operating in counter-rotating assembly.

2) The added counter-rotated rotor shows much lower performance than the initial rotor. This is reasonable as it is influenced by wake from the upstream rotor. The second rotor is able to capture 2-8 % more of total energy in the stream.

3) Single rotor turbine reaches maximum power coefficient up to 37 % at TSR 6, while CRWT shows maximum total power coefficient of 39 % at TSR 5. The improvement of power coefficient is significant at low TSR region.

This work basically aims for a small CRWT that is compact in size. The results have not yet shown significant advantages of the CRWT over the conventional single rotor turbine, but it is noticeable that power coefficient is increased by applying counter-rotating concept. In fact, there are many factors that influence the performance of counter-rotating system. Hence, further study is to be carried out to investigate more on this topic. Nevertheless, the results in this paper show high potential of CRWT for the future development of wind turbine technology.

Nomenclature

a	Induction factor
A	Swept area [m^2]
b,c,d,e,f	Velocity reduction coefficients
C_D	Drag coefficient
C_L	Lift coefficient
C_P	Power coefficient
C_Q	Torque coefficient
P	Power (W)
V	Free stream velocity [m/s]
V_d	Veloctity at turbine disc [m/s]
ρ	Air density [kg/m^3]

References

[1] Betz, A.(1919), Schraubenpropeller mit Geringstem Energieverlust, Nach.der Kgl. Gesellschaft der Wiss. Zu Gottingen, Math-Phys. Klasse, pp. 193-217.

[2] Burton, T., D. Sharpe, N. Jenkins and E. Bossanyi(2011), Wind Energy Handbook, John Wiley & Sons Ltd, ISBN 13: 978-0-471-48997-9 (H/B), pp. 42-46.

[3] Chantharasenawong C., B. Suwantragul and A. Ruangwiset (2008), Axial Momentum Theory for Turbines with Co-axial Counter Rotating Rotors, Commemorative International Conference of the Occasion of the 4th Cycle Anniversary of KMUTT, SDSE2008, pp. 2-5.

[4] Hartwanger, D. and A. Horvat(2008), 3D Modelling of a Wind Turbine Using CFD, NAFEMS Conference 2008, UK, pp. 6-7.

[5] Herzog, R., A. P. Schaffarczyk, A. Wacinski and O. Zürcher(2010), Performance and stability of a counter–rotating windmill using a planetary gearing: Measurements and Simulation, In proceeding of: European Wind Energy Conference EWEC 2010, pp. 1-7.

[6] Ingram, G.(2011), Wind Turbine Blade Analysis Using the Blade Element Momentum Method, Version 1.1, pp. 5-15.

[7] Kumar, P. S., R. J. Bensinh, A. Abraham and S. Ilangovan (2013), Computational and Experimental Analysis of a Counter-Rotating Wind System, Iournal of Scientific & Industrial Research, Vol. 72, pp. 300-306.

[8] Newman, B. G.(1986), Multiple Actuator-Disc Theory for Wind Turbine, Journal of Wind Engineering and Industrial Aerodynamics, 24, pp. 215-225.

[9] Somers, D. M.(2005), The S822 and S823 Airfoils, National Renewable Energy Laboratory (NREL), US, NREL/SR-500-36342, pp. 2-3.
[10] Tangler, J. L. and D. M. Somers(1995), NREL Airfoil Families for HAWTs, National Renewable Energy Laboratory (NREL), US, AWEA 1995, pp. 3-5.

원고접수일 : 2013년 11월 06일
원고수정일 : 2014년 01월 22일 (1차)
2014년 02월 03일 (2차)
게재확정일 : 2014년 02월 25일